Basics on Design and Analysis of SE Experiments: Widespread Shortcomings

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Content

1. Experiment distinguish hallmark
2. Good practices for running a SE experiment
   1. Definition & Operationalization
   2. Design
   3. Implementation & Execution
   4. Analysis
   5. Interpretation
   6. Packaging & Publication
3. Summary of advices
Experiments Distinguishing Hallmark

- Causality
- Control
Scientific Knowledge

- Scientific laws are patterns of behaviour
- Describe *cause-effect relationships*
- Explain
  - *why* some events are related
  - *how* the mechanism linking the events behaves
Why Experiments Are Needed

- We cannot perceive laws directly through our senses

- Two activities are necessary
  - Systematic objective observation
  - Inference of links between cause & effect
A Scientific Method

- Collection of Empirical **Data**
  - Systematic observation to appreciate the nexus

- Theoretical Interpretation of Data
  - Form a hypothesis (right or wrong) about the mechanisms relating the events

- Collection of Empirical **Data**
  - Hypothesis are permanently tested against reality to know if they are true or not
SE Experiments

- Identify and understand
  - the variables that play a role in software development
  - the connections between variables

- Learn cause-effect relationships between the development process and the obtained products

- Establish laws and theories about software construction that explain development behaviour
Experiment Definition

- **Experiment**
  - Models **key characteristics** of a reality in a **controlled environment** and manipulating them iteratively to investigate the impact of such variations and get a better understanding of a phenomenon.

- **Laboratory**
  - Simplified and controllable reality where the phenomenon under study can be manipulated.

*Other type of empirical studies do not manipulate reality, just observe it.*
Control Is The Key For Causality

- The key aspect of a controlled experiment is… **Control!!!**

- Causality is discovered through the following reasoning
  - Control voids the effect of all irrelevant variables
  - The impact we observe in the response variable is only due to the manipulated variables
Factors & Response Variables

- To gain evidence of a presumed cause-effect relationship, the experimenter
  - Manipulates
    - the independent variables
    - or factors
  - Observes changes in
    - the dependent variable
    - or response variable
Good Practices for Running a SE Experiment

1. Definition & Operationalization
2. Design
3. Implementation & Execution
4. Analysis
5. Interpretation
6. Packaging and Publication
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Definition Goal

Problem Definition
- As in any other research choose an open problem

Research goals and questions
- Causal research question
  - Does X cause Y?
  - Does X1 cause more of Y than X2 causes of Y?

Example
- Does MDD cause higher quality software than other development paradigm?
MDD Experiment Example

- Run a subjects-based experiment on MDD
  - in the context of a course about MDD
- Factor
  - Development approach
- Treatments
  - MDD
  - Control?
- Response variable
  - Quality
Constructs Operationalization

Theory

Cause Construct → Cause-Effect Construct → Effect Construct

Measurement

Treatment → Treatment-Response Construct → Response

Observation

Independent Variable → Dependent Variable
Effect Operationalization

1. Effect Variables into Response Variables
   - Higher quality software => less defects in it => Testing techniques help to identify defects
   - Effectiveness

2. Metrics Definition
   - Number of defects found
     - More defects found = more effective testing technique
     - Proportion of defects found out of those seeded

3. Instrumentation
   - Seed defects into programs
     - Which type of defects?
     - How do we generate such defects?
   - Need one or more programs
   - Subjects applying the testing techniques
     - Which type of subjects?
   - Form where subjects write down the test cases generated OR the defects found
     - Do we want the subjects running their test cases OR the experimenter?

4. Data Collection procedure
   - Number of defects identified by subjects
     - Subjects writing down the defects founded
   - Number of defects exercise by the test cases generated by the subjects
     - Subjects writing down the test cases generated

5. Measurement procedure = Metrics collection procedure
1. Cause variables into treatments
   - Factor
     - Testing techniques
   - Treatments
     - White box / Black box applied by subjects

2. Treatments definition
   - Version of the technique
   - How treatment is administer
     - Teaching?
   - Description in a “reminder sheet”
   - Otros?
Effect Operationalization: Size Example

1. Response Variable
2. Metrics Definition
3. Instruments
4. Data Collection procedure
5. Measurement (metrics collection) procedure
Effect Operationalization: Size Example

1. Variables
   - Table length

2. Metrics Definition
   - Centimeters

3. Instruments
   - Measuring tape

4. Data Collection procedure
   1. Place the beginning of the tape just at one end of the table
   2. Pull the tape until the other end

5. Measurement procedure (metrics collection)
   - Look at the number printed on the tape that matches the extreme of the table
Effect Operationalization: Quality Example

1. Variables
   - Code quality -> Functionality -> Accuracy [ISO9126]

2. Metrics Definition
   - Percentage of acceptance test cases that are successfully fulfilled
     - 1 test case per atomic requirement
     - Each test case subdivided in items
     - All items need to be passed to consider a test case satisfied

3. Instruments
   - IDE where the code developed by subjects is stored

4. Data Collection procedure
   1. For each test case
      1. Run the code

5. Measurement (metrics collection) procedure
   1. For each test case decide if it is passed
   2. Sum up the number of test cases passed
   3. Convert such a number into a proportion
Cause Operationalization
Treatment Definition

- Version of the treatment
  - What exactly is MDD?
    - NDT, WebRatio, OOHDM, OO-Method, etc
  - What exactly is traditional?
    - Model-centric?; Code-centric?; other?

- How treatment is administer
  - Teaching?

- Are treatments applied through tools?
  - Which?
Formulate Hypothesis

MDD (OO-Method w/ Integranova tool)
satisfies different amount of test cases
for small problems implemented in java
than
A model-centric (UML w/ Eclipse)
when applied by novice developers
One-tailed vs Two-tailed

- **Two-tailed hypothesis = Non directional**
  - Predicts a difference between two variables
  - Not the direction or the nature of their relationship
    - Quality(MDD) $\leq$ Quality(Model-centric)

- **One-tailed hypothesis = Directional**
  - Predicts the direction of the difference between two variables
    - A positive or negative correlation
    - Quality(MDD) $>$ Quality(Model-centric)
  - Requires previously obtained knowledge about the effect
    - Theory or evidence
Two-tailed Tests

Test statistic distribution under $H_0$
Good Practices

- Think carefully about which metrics to use
  - Metrics are not yet a solved issue in SE

- Remember to decide on the measurement process beforehand!
  - This influences the instruments

- Use two-tailed hypothesis, better than one-tailed
Good Practices for Running a SE Experiment

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Experimental Design

- Describe how the study is organized
- Identify *undesired* sources of variability
- **Iterate** improving design evaluating threats and confounding variables
Types of Design

- Depending on the number of factors and treatments a type of design is chosen
  - One factor w/ 2 treatments
  - Blocked design
  - Factorial design
    - Completely randomized design
    - Blocked factorial design
    - Fractional factorial design
    - ...
  - Repeated-measures randomized controlled trial
The key aspect of a controlled experiment is... **Control!!!**

The design of a controlled experiment is a set of strategies aiming to control

- The relevant variables (under study)
- The irrelevant variables but with known values
- The irrelevant variables with unknown values
Main Design Strategies

- **Treatments**
  - Equality inside treatments
  - Similar conditions among treatment

- **Irrelevant variables with known values**
  - Blocking
    - The non-desired variable has effect on the dependent variables, but similar effect on every treatment group
  - Block as many variables as you can

- **Irrelevant variables with unknown values**
  - Randomization
    - Assign treatments at random to experimental units to avoid the undue influence of any possible variables
  - Randomize for the rest
Example: Blocking

- **The MDD experiment with two groups**
  - Factor
    - Development paradigm
  - 2 Levels
    - MDD & Traditional

- Imagine we have experts and novices
- We blocked by experience

<table>
<thead>
<tr>
<th>Session 1</th>
<th>P1</th>
<th>MDD</th>
<th>Traditional</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>G2</td>
<td></td>
<td></td>
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<tbody>
<tr>
<td>Novices</td>
<td>Experts</td>
<td>Novices</td>
<td>Experts</td>
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Main Design Strategies

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Blocking

- Blocking is the arrangement of experimental units into groups (blocks) consisting of units that are similar to one another.
- Blocking reduces known but irrelevant sources of variation between units and thus allows greater precision in the study output.
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- Blocking reduces known but irrelevant sources of variation between units and thus allows greater precision in the study output.
- Purposely assign every value of the non-desired variable to every experimental group.
- The non-desired variable has effect on the dependent variables, but similar effect on every group (treatment).
Blocking

- Purposely assign every value of the non-desired variable to every experimental group

- The non-desired variable has effect on the dependent variables, but similar effect on every group (treatment)
Randomization

- To assign treatments at random to the experimental units
- Aims to avoid the undue influence of any possible confounders (known or unknown)
- The presence of uncontrolled confounders will tend to increase the experimental error
Randomization

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- Aims to avoid the undue influence of any possible confounders (known or unknown)
- The presence of uncontrolled confounders will tend to increase the experimental error
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- Randomization is necessary for conclusions drawn from an experiment to be correct, unambiguous and defensible
Randomization

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Iterating for Design

- Designing an experiment is an **iterative** task to reaching a trade-off among validity threats
  1. Design
  2. Evaluate issues that threaten validity

- Several design choices need to be made to limit threats to validity
  - There is not such a thing as The Perfect Experiment that avoids all validity threats
Experimenters must weigh the threats to validity and design the experiment trying to avoid them.

Those threat to validity which the experimenter suspects has failed to prevent has to be made explicit.

Good design try to avoid confounding variables.
MDD Experiment Example

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- Factor
  - Development approach
- Treatments
  - MDD
  - Traditional
- Response variable
  - Quality
1 Factor Design
2 Treatments

Pros
- Treatments comparison done through identical conditions

Cons
- 1 session, 2 groups, 1 experimental object
- Divide by two the number of subjects
  - Decreasing the sample size and therefore lowering power
- Training perspective, pairs will only practice MDD or traditional method
  - Not viable alternative in a MDD course
- Very low generalization
  - Only to one problem

Live with this depends on the sample size we have
We cannot live with this in this context
We can hardly live with this
Power relates with Type II error

Type I error
(false positive)

You’re pregnant

Type II error
(false negative)

You’re not pregnant
Paired Design
1 Object

- 2 sessions, 1 group, 1 object
- Cons
  - Threat: Learning effect on object
    - Subjects might learn the problem in the first
  - Treatments comparison in not identical conditions
    - Similar conditions: Different sessions
    - Very dissimilar conditions: Different order
- Pros
  - Biggest sample size
    - Highest power
  - Same subject under each treatments
    - Better control of subjects differences

We cannot live with this

We can hardly live with this

Great!!! 😊
Paired Design
2 objects

- 2 sessions, 1 group, 2 objects
- Cons
  - Treatments compared in different conditions
    - Similar conditions
      - Different sessions
    - Dissimilar conditions
      - Different order
      - Different problem
- Pros
  - Biggest sample size
  - Better control of subjects differences
  - Avoid learning effect on object
Cross-over
2 objects

- 2 session, 2 groups, 2 objects
- Cons
  - Session and object is confounded
    - But does not affect treatments
  - Hard to sell alternative in a MDD course
    - Specially the MDD-T order
- Pros
  - Avoid the influence of session on treatment
  - Biggest sample size
  - Better control of subjects differences
  - No learning effect on object

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<td>G1</td>
</tr>
<tr>
<td>Session 2</td>
<td>P2</td>
<td>G2</td>
</tr>
</tbody>
</table>

We can live with this

We can hardly live with this in our context
Paired
Blocked by object

- 2 session, 2 groups, 2 objects
- **Cons**
  - Session and development paradigm confounded
    - But adheres to the regular way it happens
  - Weak cheating effect on object
    - Since different treatments are being applied
- **Pros**
  - No learning effect on object
  - Biggest sample size
  - Better control of subjects differences
  - Make sense from an educational point of view

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<tr>
<td>Session 2</td>
<td>MDD</td>
<td>G2</td>
</tr>
</tbody>
</table>
Cross-over

1 object

- 2 sessions, 2 groups, 1 object
  - First, half subjects MDD, the other half T; Then, the other way around
  - Same problem in both sessions

- Cons
  - Threat: Learning effect on object
    - Subjects might learn the problem in the first session and the results obtained in the second one may depend on the knowledge obtained in the first one
  - Threat: Cheating effect
  - Low generalization for other objects
    - Results are valid for only one problem

- Pros
  - We use the biggest sample size we can
    - Highest power
  - Avoid the influence of session on treatments
Just an Example!

- Noticed these are all not the only designs
  - Cross-over with 2 objects
  - Cross-over blocked by object
  - Matched pairs designs
  - ....

- We could have followed other reasoning
Design is Experiment-dependent

- The best design for certain situation can be the worst in others
  - Sample size was a problem in our experiment
    - If it is not, then first design could work
  - Sequential application of treatments is ok in our context (due to technology being tested)
    - For others, for example testing, application of treatment in only one order would be a big threat
Good Practice

- Do not copy your design from others!!
  - The sources of variability is particular to every experiment
  - You need to iteratively think about your design, evaluate threats and modify it selecting the best you can
  - Include the iterative process and decision in the paper!
Good Practice

- Replicate your own experiment
  - If you do it identically
    - Sample size is increased
  - If change something
    - Some threats to validity can be mitigated
      - In the example
        - Order threat
        - Low generalizability
        - ...

Good Practice

- Make always a previous demographic questionnaire
  - Helps on blocking
  - For post-hoc analysis
Good Practices for Running a SE Experiment

1. Definition & Operationalization
2. Design
3. Implementation & Execution
4. Analysis
5. Interpretation
6. Packaging and Publication
Implementation & Execution Goals

- **Implementation**
  - Instantiate the experimental design, so can be executed
- **Tasks**
  - Design all required instruments
    - Questionnaires, protocols and tools
  - Prepare all necessary material
    - Guidelines, document templates, specifications, codes and tools
- **Execution**
  - Run the experiment
Good Practice

- Run a Pilot
  - To be sure instruments work well
  - To assure explanations are clear
  - …
  - Things usually do not go out as expected 😞
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Analysis Goal & Tasks

- Analyze collected data for
  - Describing sample
  - Testing hypothesis

- Tasks
  1. Descriptive statistics
  2. Select statistical test
  3. Hypothesis testing
  4. Power analysis
  5. Effect size calculation
Statistical Test Selection

- Statistical tests
  - Exist for different purposes
  - Have different preconditions
  - Have different power

- Your data set must fulfill the test assumptions on
  - Experimental design
  - Distribution of data

- Choosing appropriate statistical test is key to get a reliable rejection or not rejection of the null hypothesis
# Statistical Test Selection

<table>
<thead>
<tr>
<th>Number of variables</th>
<th>Subjects in condition</th>
<th>Parametric Test</th>
<th>Non parametric Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>One variable: two treatments</td>
<td>Independent</td>
<td>Independent t-test</td>
<td>Mann-Whitney U test</td>
</tr>
<tr>
<td></td>
<td>Dependent</td>
<td>Paired t-test</td>
<td>Wilcoxon matched pairs test</td>
</tr>
<tr>
<td>One variable: &gt; 2 treatments</td>
<td>Independent</td>
<td>One factor independent ANOVA</td>
<td>Kruskal-Wallis-One way ANOVA</td>
</tr>
<tr>
<td></td>
<td>Dependent</td>
<td>One factor repeated measures ANOVA</td>
<td>Friedman ANOVA</td>
</tr>
<tr>
<td>Two or more treatments</td>
<td>Independent/Dependent</td>
<td>Variation of ANOVA-Analysis</td>
<td>-</td>
</tr>
</tbody>
</table>
Parametric vs. Non-parametric

- Select statistical test considering data distribution
  - Normal distribution
    - Parametric tests
  - Non-normal or ordinal/nominal distribution
    - Non-parametric tests
- Do not assume normality (using the Central Limit Theorem)
  - Irrespective of the distribution of the parent population - given that its mean $m$ and a variance $s^2$, and so long as the sample size $n$ is large, the distribution of sample means is approximately normal with mean $m$ and variance $s^2 / n$
  - Consider non-parametric tests
    - SE experiments have small sample sizes
- But neither use always non-parametric test
Hypothesis Testing

1. Formulate the alternative and null hypothesis
2. Select statistical test considering data distribution
   - Normal distribution
     - Parametric tests
   - Non-normal or ordinal/nominal distribution
     - Non-parametric tests
3. Select significance level ($\alpha$-value) and perform power analysis
   - $\alpha$ conventionally 0.05 or 0.01
   - Power = $1 - \beta$ ($\beta$ conventionally 0.2)
     - Determine optimal sample size based on $\alpha$, effect size and power
     - Determine $\alpha$ based on sample size, effect size and power
Perform Power Analysis

<table>
<thead>
<tr>
<th>Decision</th>
<th>In the population …</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H_0$ is true</td>
</tr>
</tbody>
</table>
| $H_0$ is not rejected | **Correct** outcome  
True negative | **Type II error**  
False negative |
| $H_0$ is rejected | **Type I error**  
False positive | **Correct** outcome  
True positive |
Sample Size & Statistical Power

- The foolish astronomer
  - An astronomer decides to build a telescope to study a distant galaxy
  - He foolishly builds it on the basis of available funds, rather than on the calculations of the needed power to actually see the galaxy
  - He orders the biggest telescope he can afford and hopes for the best...
Understanding the Outcome

- If null-hypothesis is **rejected**
  - There is an effect

- If null-hypothesis is **not rejected**
  - It is not possible to conclude there is no effect!
  - There is not sufficient evidence to accept there is an effect
Three Critical Parameters

- **Statistical significance**
  - A result is significant because it is predicted as unlikely to have occurred by chance alone
  - The observed effect seems to have a cause

- **Power**
  - The probability that a test finds there is no difference between treatments when there is

- **Effect size**
  - Magnitude of the results
  - Which is the size of the improvement?
Good Practice

- Learn about analysis
  - Get the advice of an expert

- Check the proper analysis for your design

- Do not always apply the same type of tests
  - Check tests assumptions on data distribution

- Provide the three parameters
  - Significance, power, effect size
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Interpretation Goal

- Answering research questions

- Statistical testing is just the means to an end
  - Not an end in itself!!

- More difficult than running statistical tests
  - Interpretation of the results
  - What does the results mean?
Results Interpretation

Theory

Measurement

Observation

Cause Construct

Treatment

Independent Variable

Treatment-Response Construct

Effect Construct

Response

Dependent Variable
Good Practice

- Do not forget to interpret the results and close the circle!
- An experiment does not only give an output of a statistical test, you need to give an answer to the research question taking into account
  - The statistical issues
    - hypothesis test output, power, effect size
  - But also
    - Populations (subjects, objects), experiment protocol, observation of subjects, acontecimientos, …
Good Practices for Running a SE Experiment

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Laboratory Package

- Motivating and enabling replication
  - Enabling independent confirmation of results
  - Making study design available for further investigation in different contexts

- Detailed account that allows replication
  - Measures, questionnaires, surveys, interview protocols, observational protocols, transcriptions, tape records, video record, pictures, …
Make your Results Public

- Presenting, sharing and spreading results
  - For community building a body of knowledge
  - Enabling review, discussion and challenge of results

- Follow guidelines to compose your manuscript
  - Jedlitschka
Good Practice

- Make an experimental package for others to replicate your experiment
  - The proper content for a lab package in SE is not solved yet
  - Not only materials should be there but more info on the experiment to be repeated

- Follow guidelines when reporting an experiment
Summarizing
Good Practices

- **Operationalization**
  - Think carefully about metrics to use
  - Decide before hand on the measurement process
  - Use two-tailed hypothesis

- **Design**
  - Do not copy your design from others!
  - Replicate your experiment
  - Make always a demographic questionnaire

- **Implementation**
  - Run a pilot

- **Analysis**
  - Learn about tests or get the advice of an expert
  - Be sure to correctly interpret the tests outcome
  - Provide significance, power and effect size

- **Interpretation**
  - Give answer to the research question

- **Packaging**
  - Made public at the web a replication package

- **Publication**
  - Follow guidelines
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